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13. ABSTRACT *(Maximum 200 words)*

This five year project has brought together researchers in nonlinear control theory (University of California and Caltech) and aeroengine dynamics and control (MIT) to develop new techniques for robust nonlinear Control of aeroengines. Technology transfer to the commercial sector has been achieved through strong and synergistic coupling with Pratt &: Whitney (P&:W) via United Technologies Research Center (UTRC). The specific application areas addressed were active control of. first, compression system rotating stall and surge, and second, blade flutter and forced vibration. These complex physical phenomena, which bear heavily on engine safety and performance, are arguably the most critical considerations in modern aeroengine design. The outcomes of this project are new tools and methods promising to improve both operability and reliability, of military and commercial aeroengines through robust nonlinear control. A highly integrated multi-disciplinary effort has successfully interlaced ideas and results from fluid dynamics, structural dynamics, experiments, and nonlinear control theory. For the highly nonlinear behavior associated with rotating stall and large disturbances new analytical, numerical, and experimental nonlinear techniques have been developed, transitioned to the industrial partner and widely dis-seminated to the engineering community. The results have appeared in over 40 journal papers, 50 conference proceedings, as well as in 2 patents [1.2]. Among the important spin-offs of this project are the new AFOSR flow control and mixing projects by M. Krsite. I. Mezic, and B. Bamieh. They are now better prepared to broaden the scope of control theory as a vital enabling technology.

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ROBUST NONLINEAR CONTROL OF STALL AND FLUTTER IN AEROENGINES

AFOSR-PRET F49620-95-1-0409

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1 Objectives

This five year project has brought together researchers in nonlinear control theory (University of California and Caltech) and aeroengine dynamics and control (MIT) to develop new techniques for robust nonlinear control of aeroengines. Technology transfer to the commercial sector has been achieved through strong and synergistic coupling with Pratt & Whitney (P&W) via United Technologies Research Center (UTRC). The specific application areas addressed were active control of, first, compression system rotating stall and surge, and second, blade flutter and forced vibration. These complex physical phenomena, which bear heavily on engine safety and performance, are arguably the most critical considerations in modern aeroengine design.

The outcomes of this project are new tools and methods promising to improve both operability and reliability of military and commercial aeroengines through robust nonlinear control. A highly integrated multi-disciplinary effort has successfully interlaced ideas and results from fluid dynamics, structural dynamics, experiments, and nonlinear control theory. For the highly nonlinear behavior associated with rotating stall and large disturbances new analytical, numerical, and experimental nonlinear techniques have been developed, transitioned to the industrial partner and widely disseminated to the engineering community. The results have appeared in over 40 journal papers, 50 conference proceedings, as well as in 2 patents [1, 2]. Among the important spin-offs of this project are the new AFOSR flow control and mixing projects by M. Krsitc, I. Mezic, and B. Bamieh.

The educational impact has also been tremendous. More than 20 doctoral and postdoctoral students have been challenged and inspired by complex flow control and aeroelastic phenomena. They are now better prepared to broaden the scope of control theory as a vital enabling technology.

2 Accomplishments

2.1 Surge and Stall Control

Compression system stall and surge are instability phenomena which severely limit engine performance. To reduce the effects of potentially destabilizing disturbances, the jet engine industry has traditionally designed compressors to operate away from the peak operating point. The goal of

active control is to recover the maximum performance by stabilizing the peak operating point with feedback. For fighter aircraft this may lower gross takeoff weight by as much as 16%. It may also significantly improve the efficiency and safety of commercial aircraft.

Throttle Bleed: Before the PRET project started, a possibility to control rotating stall had been successfully demonstrated in experiments by Paduano[1] using inlet guide vanes, and by Day[2] using air injection. The PRET researchers were motivated by the aeroengine industry to consider controllers with the existing technology of bleed valve actuation. Because engine bleeds are found in locations consistent with the throttle control of the low order Moore-Greitzer[3] model, the PRET project began with throttle control studies.

For actuation with throttle bleed Krstic, Fontaine, Paduano and Kokotovic [3] developed nonlinear controllers which unlike previous controllers, achieved global stability with fewer sensing requirements. This initial result highlighted the advantage of backstepping over other nonlinear designs. Rather than cancelling all of the system nonlinearities, backstepping designs identify useful nonlinearities and employ them in the stabilization of the compressor. To reduce the need for detailed knowledge of the compressor characteristic Sepulchre and Kokotovic [4] analyzed the effect of its shape. Banaszuk and Krener [5] followed with a graphical backstepping design which avoided the use of an analytical description of the compressor characteristic.

Humbert and Krener [6] explored the dynamics and control of multi-mode Moore-Greitzer compressor models. To avoid complex higher order models, while retaining their accuracy, Hauksson and Fontaine [7] developed a low order model with a single trapezoidal stall cell "mode." Their model matched experimental data with accuracy comparable to that achieved with much higher order models.

In parallel with the study of lower order models, a major effort was directed to analysis and control of infinite dimensional compressor models. Hauksson and Birnir [8, 9] showed that the Moore-Greitzer PDE model exhibits a global, finite-dimensional attractor, which justifies finite dimensional truncations. In a comprehensive PDE optimal control study Banaszuk, Mezic and Hauksson [10] extended the backstepping methodology to the infinite dimensional model. They designed a throttle controller that only used feedback from pressure and mean flow, and achieved global asymptotic stability of the closed loop PDE model.

Wang and Murray [11, 12] investigated the effects of noise and actuator limitations on compressor control. They used a bifurcation analysis to graphically describe the quantitative trade-offs between valve limitations and compressor operability. In addition, Larsen, Coller, Sepulchre and Kokotovic [13] and Coller and Larsen [14] studied the way in which bleed valve actuation modified the bifurcation structure of the compressor dynamics.

Air Injection: Limitations observed in throttle bleed experiments also motivated research in the direction of air injection. Air injection influences compressor dynamics more quickly, and unlike throttle bleed, influences the circumferential component of the mass flow. The first step toward air injection controllers was the addition of the mass and momentum effects of the injectors to the Moore-Greitzer PDE. With the inclusion of these effects, the resulting single mode truncation was shown to have qualitatively different control properties. In particular, equilibria on the axisymmetric characteristic that were not controllable with throttle bleed, were controllable with air

[1] J. Paduano, L. Valvani, A. Epstein, E. Greitzer, and G. Guenette. "Modeling for control of rotating stall." *Automatica*, 30(9):1357–1373, 1994.

[2] I. Day. "Active suppression of rotating stall and surge in axial compressors." *ASME J. of Eng. for Power*, 115(1):40–47, 1993.

[3] F. K. Moore and E. M. Greitzer. "A theory of post-stall transients in axial compression systems: Part I - development of equations." *Journal of Engineering for Gas Turbines and Power*, 108:68–76, January 1986.

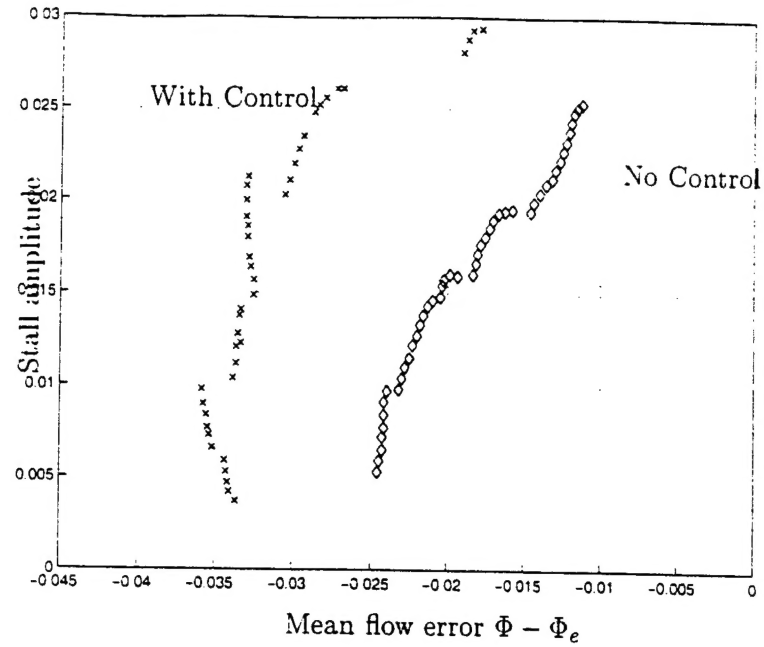

Figure 1: Increase of stability region with a nonlinear controller

injection.

Nonlinear air injection controllers were designed, implemented, and experimented with by Behnken. D'Andrea and Murray [15, 16] at Caltech and also by Protz [17] at MIT. Yeung, Behnken and Murray [18, 19] showed that it is possible to simultaneously combine air injection for stall control and bleed valves for surge control. Yeung and Murray [1] further demonstrated that the axisymmetric air injection reduced the actuator bandwidth and rate limit requirements for control of rotating stall with bleed valves. Yeung [20] introduced a model that cast the effect of air injection on compressor performance as incidence angle and losses management. In simulations and experiments, he investigated controllers for axisymmetric and non-axisymmetric injection on high B and low B compressors. Air injection research also contributed to the analysis of inlet distortion, one of the most common causes of compressor instability. Protz [17] and Yeung [20] investigated robustness with respect to both static and rotating distortion.

Interstage Bleed: Experiments with air injection confirmed that its advantage over throttle bleed is due to its control authority over the circumferential component of the mass flow, and its proximity to the compressor stages. However, air injection is not popular in industry because of the need to retrofit engines with an independent source of compressed air, or a complicated air recirculation mechanism.

A new, more appealing actuation strategy uses a ring of bleed valves in close proximity to the compressor stages. It achieves the relative simplicity of throttle control while retaining some of the control authority of air injection. With an array of four bleed valves placed after the last stage of an MIT low speed compressor, Fahim [21] was able to stabilize rotating stall. A difficulty with this location is the high temperature of the mass flow exiting the compressor.

Current research is focused on interstage bleed, that is the bleeding of cooler air from the mid-section of the compressor. Liao [22] included the effect of asymmetric interstage bleed control in the Moore-Greitzer PDE model and derived the corresponding single mode truncation. Analyzing this model, Fontaine, Liao, Paduano, and Kokotovic [23] established that nonlinearities in the

control input matrix prevented linear control from achieving a satisfactory region of attraction. However, with a simple nonlinear extension of the original linear design they were able to stabilize the pressure peak with an acceptable region of attraction.

Controllers with a ring of bleed valves have been experimentally verified by Liao [48] and Fontaine, Liao, Paduano, and Kokotovic [24] on the three-stage, low speed compressor at MIT. Figure 1 shows typical experimentally obtained data points on the boundary of the region of attraction: uncontrolled with a $\diamond$ and controlled with an "x". In this experiment the stability boundary achieved with a relatively simple Lyapunov-based nonlinear controller is far beyond the boundary for the uncontrolled compressor.

2.2 Flutter

Having developed and demonstrated a number of new modeling and control techniques for active control of stall and surge, the PRET team turned much of its attention to active control of flutter. While significant progress was made in the development of tools and concepts, difficulties in fabrication of composite transonic rotors, and in securing test facilities for transonic compressor tests, limited the scope of flutter research to preliminary studies and development of active rotor fabrication methodologies. In this section we summarize modeling and control design results, and then describe experimental efforts.

Two levels of flutter modeling were pursued. In cooperation with UTRC, a low order model was developed that extends the Moore-Greitzer model to include blade flexibility. This model elucidated the interactions between rotating stall and flutter stabilization [41]. In particular, we showed that off-blade actuation and sensing are feasible for control of fundamental flutter modes, and that rotating stall feedback control could potentially destabilize flutter modes. Thus integrated control law design is necessary. A methodology to study the sensitivity of the Campbell diagram to compressor design variations was also demonstrated [46].

To study transonic flutter and forced response in more detail, a CFD-based modeling approach was adopted. Using Proper Orthogonal Decomposition (P.O.D.) methods combined with a unique application of Arnoldi vectors, the first reduced-order model of a transonic Euler flutter solution was obtained [42, 43]. These methods encapsulate unsteady CFD results into models which can be interconnected via boundary conditions to study interactions between blade rows, forced response effects, and mistuning. Several aeromechanics applications of the model order reduction procedure were demonstrated, including forced-response predictions with improved accuracy over traditional methods, multi-stage stability calculations, and models suitable for mistuning studies [43].

Mistuning was a major focus of the aeromechanics control efforts. Using symmetry principles, the concept of robust mistuning was demonstrated. Intentional mistuning results in a configuration that is more robust to unintentional variations in blade properties. Optimal mistuning strategies were developed to both increase the stable operating range of rotors (passive flutter control), and to reduce the resonant behavior that often arises due to unintentional mistuning [44]. Using the low-order models described in the previous section, these methods were validated at an industrially-acceptable level of accuracy. Experimental demonstration is still being pursued.

Development of methods which combine expertise from both the fluids/CFD and the dynamical systems community represents one of the major successes of the PRET program. Our CFD specialists recognized that the input-output approach to modeling (common in systems theory) is powerful way to tackle systems which are otherwise computationally intractable. When combined with model-order reduction procedures, high-accuracy models of aeroelastic systems were made accessible to systems theory specialists. The fluid/aeroelasticity community, in turn, was provided

with a new perspective on the mistuning problem that promises to make intentional mistuning a much more systematic process.

Another achievement of the PRET program was the design and prototyping fo an active rotor blade, for system identification and control of the unsteady aerodynamics associated with flutter and forced response. Primary emphasis was on a composite transonic rotor blade, with embedded graphite-epoxy spars. The spars were actuated by piezos to cause the blade to bend and/or twist on command. Fabrication techniques for the graphite-epoxy core, a foam outer covering, and associated sensing and actuation were developed. Calculations and lab tests [45] were performed to insure the spars had sufficient strength, that piezos would survive the high stress levels, and that actuation in the rotating environment is possible. Identification and estimation methods were applied to the actuated spar system to determine effectiveness of bending/twist actuation [47].

At this writing, a blade design with the desired capability has been completed, and most of the components tested. This was enabled by a DURIP grant, which funded the construction of an evacuated spin test facility for scaled transonic rotors. In this facility, testing of the structural integrity and dynamical properties can now be performed and used to validate the mistuning concepts described above.

2.3 Experiments

Most modeling, analysis, and control investigations in this program were accompanied by experiments performed on facilities at Caltech and MIT. Researchers from every site participated in experiments at these universities, resulting in significant interaction between experiment and theory.

The Caltech low-speed compressor provided a fast-prototyping facility for studying various actuation and nonlinear control concepts. This facility was configured for control using both inlet injection and downstream bleeds. The MIT low-speed compressor was modified to represent a multi-stage compressor feeding a large plenum, so that the overall system has a large B parameter. This compressor was outfitted with distributed downstream bleed valves, for testing of the most likely implementation strategy for active control in real engines.

The most realistic experimental facility was the Allied Signal LTS-101 gas producer, which was modified during the PRET program to allow more complex identification and control studies. Improving the set-point hardware and experimental procedures in this facility was instrumental in the demonstration of robust control of surge in this engine [49].

Finally, a new evacuated spin test facility for testing aero-structures was designed and built. This facility was designed to operate up to 20,000 rpm, consistent with scaled transonic compressors with tip Mach numbers of 1.5. The facility incorporates a high-voltage slip ring to allow on-blade piezo actuation, as well as tip clearance deflection sensors for monitoring blade vibration.

Thanks to the strong interaction between theory and experiment, new experimental methodologies were developed. For instance, one of the most important concepts for understanding the nonlinear dynamics of compression systems is the compressor pressure-flow characteristic. This curve is especially important near and below the peak pressure rise; however it is impossible to directly measure below the peak pressure-rise massflow point, because the system is not stable in this regime. A novel method for experimental estimation of this function was developed at Caltech, and used for the compressors at both Caltech and MIT [15, 17].

Methods for experimental determination of nonlinear stability properties were also developed. The importance of the effect of distortion on compressor stability has long been understood; however purely static methods for determining the effects of distortion are currently used in industry. A

measure based on theoretical Lyapunov functions for rotating stall dynamics was used to quantify the impact of distortion on stability, and to measure the improvement afforded by active control of rotating stall [17]. Similarly, methods to induce zeroth and first harmonic disturbances in the compression system were developed [48]. These methods allow the domain of attraction of the compression system to be estimated experimentally.

Stability limits in actively controlled compressors are often determined by actuator rate and saturation levels. Thus careful experiments to link steady-state measured performance, actuator constraints, and measured nonlinear stability characteristics were carried out [12]. These experiments clearly showed the role of actuator limits in compressor stability, and validated the theoretical predictions. This is an example of the interplay between theoretical and experimental research that highlighted the PRET effort, and yielded important results for both the control community and industry.

A final example of experimental methodologies demonstrated under the PRET program was the implementation of robust H-infinity methods in a full-scale a gas turbine engine. System identification procedures were applied to the Allied Signal LTS-101 gas generator, yielding multivariable models of the input-output, acoustically coupled, surge dynamics [49]. Smith's approach for H-infinity design, which explicitly accounts for eigenvalue uncertainty, was used to design control laws. These control laws were then demonstrated to stabilize surge without destabilizing acoustical modes. Prior to the application of robust control methods, successful stabilization of surge in such full-scale devices had not been achieved.

2.4 Theoretical Advances

While highly focused on jet engine applications, this research has also advanced several areas of control theory, dealing with constructive robust designs. A representative selection of such results is listed below.

Locally optimal backstepping[26, 27, 28] is a new result that combines robust optimal linear designs with global nonlinear designs and helps avoid wasteful cancelations of useful nonlinearities. Original backstepping designs allowed a lot of freedom for construction of control Lyapunov functions. When these functions are restricted to be the value functions of optimal control or game problems, the designed nonlinear feedback system is "inverse optimal" with quantifiable stability margins. Ezal, Pan and Kokotovic [27] have now enhanced the backstepping design by making it not only globally inverse optimal, but also locally optimal with respect to a prescribed LQ or H_∞ optimality criterion.

Robustness of backstepping control laws to unmodeled dynamics was studied by Arcak and Kokotović [29, 30] who developed robust redesigns of recursive nonlinear designs. A recent redesign by Arcak, Teel and Kokotović [31, 32] removed the relative degree and minimum phase assumptions on the unmodeled dynamics that had been a long standing obstacle in robust nonlinear control.

Passivation designs have been advanced by Larsen and Kokotović [33, 34] for nonlinear multiple-input systems combining single-input single-output design tools. In the new "indirect passivation," [35] one control is used to arrive at a system architecture for which passivation can be used to design a control law for the second control. This approach has been illustrated by a passivation design of a simplified model of turbocharged diesel engine.

Output feedback designs have been extended to systems with monotonic nonlinearities by Arcak and Kokotović. They developed a new nonlinear observer [36, 38] and combined it with backstepping for the output-feedback stabilization of a class of nonlinear systems which incorporates general models of mechanical systems. Kang and Krener have developed a new backstepping method for

constructing nonlinear observers. The method is global with respect to the original dynamical system but only local in the error dynamics. The on-line computational burden is less than that of an extended Kalman filter, and the local exponential convergence is guaranteed by a Lyapunov argument.

Bifurcations and normal forms have been extended by Richard Murray and co-workers to control of systems that contain a linearly unstabilizable mode. They have characterized systems which can be controlled by creation of a (small) stable limit cycle, and have also shown that in certain instances bifurcation control can extend the stability boundary even in the presence of actuator limits. Larsen, Coller, Sepulchre and Kokotovic [13, 14] discovered that an actuator induced bifurcation may increase the effectiveness of bleed valve control for a compressor model.

Spatial invariance has been identified by Bamieh [39, 40] as a fundamental property of several important flow control problems. He has pursued the development of constructive design and analysis techniques for distributed control with arrays of sensors and actuators. These techniques dramatically simplify optimal controller architecture and reduce the communication requirements between sensors and actuators in the array.

3 Interactions

The PRET program included substantial interactions between the academic members of the team as well as United Technologies. For the first two years of the program, workshops were held approximately twice a year, with attendance by all of the participating institutions, the Air Force Research Lab, and outside researchers. These workshops served as a mechanism for learning about some of the important features of the stall, surge, and flutter problems in aeroengines as well describing methodologies and results. In addition to the workshops, bi-weekly conference calls between the PIs were used to maintain frequent contact and identify promising areas for collaboration.

There was also substantial interaction with the United Technologies Research Center, through extended visits of faculty, students and postdocs. The following list gives a brief summary of some of the longer exchanges of personnel within the program:

- Maverick Wong (MIT): Summer 1996 at UTRC
- Ben Shapiro (Caltech): Summer 1996 and summer 1997 at UTRC
- Yong Wang (Caltech): 1998-99 academic year at MIT, with several visits to UTRC
- Sean Humbert (Caltech): Summer 1997 at UTRC and regular trips during 1998 to work on flow control (directed synthetic jets)
- Simon Yeung (Caltech): Regular trips to UTRC during 1997 to work on flow control
- Dan Fontaine (UCSB): Summer 1997 at UTRC
- Richard Murray (Caltech): UTRC Consultant from 1996-1998, Director of Mechatronic Systems (full time) from 1998-1999
- Jim Paduano (MIT): Consultant for UTRC in 1999

In addition, through the activities associated with the PRET program, UTRC has established research interactions with Miroslav Krstic (UCSD), Igor Mezic (Harvard), and Brianno Coller (UIC).

There were several major research transitions that occurred over the duration of the program.

Mistuning for Passive Control of Flutter Both Ben Shapiro and Karen Willcox presented their methods for reduced-order modeling, analysis and optimization of mistuning in transonic compressors to personnel at UTRC and GE. This interaction prompted internal efforts at UTRC in the areas developed under the PRET effort. To enable further transition. Ben Shapiro's program MAST (Mistuning Analysis by Symmetry Techniques) has been delivered to Pratt & Whitney, and can be obtained as shareware at www.enae.umd.edu/home by following the links faculty → shapiro.

Active Control of Stall on NASA High Speed Compressor Under combined support from NASA and AFOSR, implementation of active control concepts in a transonic compressor was pursued. In addition, Chris van Schalkwyk, an AFOSR-sponsored student now working at Scientific Systems, participated in NASA-sponsored active control tests in the AFRL Compressor Research Facility, demonstrating actuation and control of a GE two-stage military fan with inlet distortion.

There were numerous other research transitions throughout the five year program. Due to space constraints. these are not listed here. Additional information may be found on the PRET web site or in previous annual reports. Most important for the long term impact of the PRET program is the transition of personnel into industrial positions related to the work performed under the contract. These include:

- Andrzej Banaszuk: Senior Research Engineer at UTRC, after postdoctoral position with Art Krener at UC Davis
- Simon Yeung: Research Engineer at GE Corporate Research after PhD at Caltech
- Sean Humbert: Engineer at Pratt & Whitney (Chemical Sciences Division) after MS at Caltech.
- Karen Willcox: Will spend one year in industry before returning to the MIT Aero-Astro department as a junior faculty member.

4 Personnel Supported

Faculty:
Petar V. Kokotovic. PI. UCSB
Arthur Krener. PI. UC Davis
Richard Murray, PI. Caltech
James D. Paduano, PI. MIT
Bassam Bamieh. UCSB
Wei Kang. UCD
MingQing Xiao. UCD
Post-Doctorates:
Andrzej Banaszuk. UCD
Brianno Coller. Caltech
Karen Willcox. MIT
Laurent Didierjean. MIT
Zhongwei Li. MIT
Antonio Loria. UCSB
Elena Panteley. UCSB
Julio Braslavsky, UCSB
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Kenan Ezal, UCSB
Hoskuldur Hauksson. UCSB
Michael Larsen, UCSB
Murat Arcak, UCSB
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Maverick Wong, MIT
Waleed Farahat, MIT
Ahmed Fahim, MIT
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Jin-Young Hong, MIT
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Debashis Sahoo. MIT
Shengfang Liao, MIT
Ammar Alnahwi, MIT
Vishal Saxena, MIT
Gordon Maahs, MIT
Eric Nelson, MIT
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Arturo Duarte, UCD
Allen Tesdall. UCD
Carmeliza Navasca, UCD
Eric Lau. UCD
Long Li, UCD
Simon Yeung, Caltech
Yong Wang, Caltech
Robert Behnken, Caltech
Raffaello D'Andrea, Caltech
Ben Shapiro, Caltech
Sean Humbert, Caltech

Selected References

[1] S. Yeung and R. Murray. "Actuator bandwidth and rate limit reduction for control of compresor rotating stall." U.S. Patent Application, October 1997. Serial No. 60/037,774.

[2] A. Krener and M. Krstic, "Method and Apparatus for Predicting and Stabilizing Compressor Stall." U.S. Patent. 2000.

[3] M. Krstić, D. Fontaine, J. Paduano, and P. Kokotović. "Useful Nonlinearities and Global Stabilization of Bifurcations in a Model of Jet Engine Surge and Stall." *IEEE Trans. on Automatic Control*, Vol. 43 No. 12. pp. 1739-1745, 1998.

[4] R. Sepulchre and P. Kokotovic. Shape signifiers for control of a low order compressor model. *IEEE Trans. Auto. Contr.*, 43(11):1643–1648, 1998.

[5] A. Banaszuk and A. Krener "Design of controllers for MG3 compressor models with general characteristics using graph backstepping," *Automatica*, 35(8):1343–68, 1999.

[6] J. Humbert and A. Krener, "Dynamics and control of entrained solutions in multi-mode Moore-Greitzer compressor models," *Int. J. of Control*, 71, pp. 807-821, 1998.

[7] D. Fontaine. *Nonlinear Control of Axial Flow Compressors*. PhD thesis, UCSB, 2000.

[8] B. Birnir and H. Hauksson. "A finite dimensional attractor of the Moore-Greitzer PDE model," *SIAM J. Appl. Math.*, 59(No. 2):636–650, 1998.

[9] H. Hauksson. *The Basic Attractor of the Viscous Moore-Greitzer Equations*. PhD thesis, Univ. Calif. Santa Barbara, 1998.

[10] A. Banaszuk, H. Hauksson, and I. Mezic. "A backstepping controller for a nonlinear partial differential equation model of compression system instabilities," *SIAM J. Contr. Optimiz.*, 37(5):1503–1537, 1999.

[11] Y. Wang and R. Murray. "Effects of noise, magnitude saturation, and rate limits on rotating stall control," In *36th Conference on Decision and Control*, pages 4682–4688, 1997.

[12] Y. Wang and R. Murray. "Effects of magnitude saturation in control of bifurcations," In *IFAC World Congress*, 1999.

[13] M. Larsen, B. Coller, R. Sepulchre, and P. Kokotovic. "Dynamic control of axial compressors," In *Conference on Control Applications*, pages 663–670, 1997.

[14] B. Coller and M. Larsen. "Beneficial actuator-induced bifurcations in compressor control," In *American Control Conference*, pages 1994–1999, 1998.

[15] R. Behnken. *Nonlinear Control and Modeling of Rotating Stall in an Axial Flow Compressor*. PhD thesis, Caltech, 1996.

[16] R. D'Andrea, R. Behnken, and R. Murray. "Rotating stall control of an axial flow compressor using pulsed air injection," *J. of Turbomachinery*, 119(4):742–52, 1998.

[17] J. Protz. *Nonlinear active control of rotating stall and surge*. Master's thesis, MIT, 1995.

[18] B. Behnken and R. Murray. "Combined air injection control of rotating stall and bleed valve control of surge." pages 987–992, *1997 American Control Conference*.

[19] S. Yeung and R. Murray. "Simultaneous stabilization of stall and surge via axisymmetric bleed and air injection." In *Conference on Control Applications*, 1998.

[20] Simon Yeung. *Nonlinear Control of Rotating Stall and Surge with Axisymmetric Bleed and Air Injection on Axial Flow Compressors*. PhD thesis, Caltech, 1998.

[21] A. Fahim. *Experimental evaluation of asymmetric bleed actuation for rotating stall and surge control*. Master's thesis, MIT, February 1998.

[22] D. Fontaine, S. Liao, P. Kokotovic, and J. Paduano. "Two dimensional, nonlinear control of an axial flow compressor model," *Automatica*. Submitted.

[23] D. Fontaine, S. Liao, J. Paduano, and P. Kokotovic. "Two dimensional, nonlinear control of an axial flow compressor." pages 921–926. *IEEE Conference on Control Applications*, 1999.

[24] D. Fontaine, S. Liao, P. Kokotovic, and J. Paduano. "Nonlinear control experiments on an axial flow compressor." In *Conference on Decision and Control*, 2000.

[25] Y. Wang, J. Paduano, and R. Murray. "Nonlinear control design for rotating stall with magnetic bearing actuators." In *Conference on Control Applications*, pages 730–736. IEEE, 1999.

[26] K. Ezal. *Disturbance Attenuating Control of Nonlinear Systems with Local Optimality*. PhD thesis, UCSB, 1999.

[27] K. Ezal, Z. Pan, P.V. Kokotovic, "Locally Optimal Backstepping Design", *Conference on Decision and Control*, 1997, pp. 1767-1774.

[28] K. Ezal, Z. Pan, P. Kokotovic, "Locally Optimal and Robust Backstepping Design", *IEEE Transaction on Automatic Control*, 2000.

[29] M. Arcak, M.M. Seron, J.H. Braslavsky, and P.V. Kokotović. "Robustification of backstepping against input unmodeled dynamics," To appear in *IEEE Transactions on Automatic Control*.

[30] M. Arcak, , and P. Kokotović. "Robust nonlinear control of systems with input unmodeled dynamics," To appear in *Systems & Control Letters*, 2000.

[31] M. Arcak, A.R. Teel, and P.V. Kokotović. "Robust nonlinear control of feedforward systems with unmodeled dynamics," To appear in *Automatica*, 2000.

[32] M. Arcak, A. Teel, and P. Kokotović. "Robust nested saturation redesign for systems with input unmodeled dynamics," In *Proceedings of the 2000 American Control Conference*, pages 150–154, Chicago, IL, 2000.

[33] M. Larsen and P. Kokotović, "Feedback passivation as a tool for stabilization of partially linear composite systems," *1999 Conference on Decision and Control*.

[34] M. Larsen, M. Janković and P. Kokotović "Master-slave passivity design for stabilization of nonlinear systems," *Proc. of the 38th American Control Conference*, 1999.

[35] M. Larsen, M. Jankovic, and P. Kokotovic, "Indirect Passivation Design: A Diesel Engine Case Study," *Automatica*, 2000.

[36] M. Arcak and P.V. Kokotović, "Observer based stabilization of systems with monotonic nonlinearities," *Asian Journal of Control*, vol. 1, pp. 1–7, 1999.

[37] A. J., Krener, "A Lyapunov theory of nonlinear observers," *Stochastic Analysis, Control, Optimization and Applications*, Birkhauser, Boston, pp. 409-420, 1999.

[38] M. Arcak and P.V. Kokotović. "Nonlinear observers: A circle criterion design," In *Proceedings of the 38th IEEE Conference on Decision and Control*, pages 4872–4876, Phoenix, AZ, 1999.

[39] B. Bamieh, F. Paganini and M.A. Dahleh, "Optimal Control of Distributed Actuator and Sensor Arrays", *Proc. SPIE 5'th Anniversary International Symposium on: Smart Structures and Materials*, 1998.

[40] B. Bamieh, F. Paganini and M.A. Dahleh, "Distributed Control of Spatially Invariant Systems", *IEEE Trans. Automatic Control*.

[41] J. Hong, M. Wong, J. Paduano, "Modeling For Control of Compressors with Aerodynamic And Aerostructural Instabilities," *Proc. of the US-Japan Seminar on Abnormal Flow Phenomena in Turbomachinery*, 1998. Japan.

[42] K. Willcox, J. Peraire, and J. White, "An Arnoldi Approach for Generation of Reduced Order Models for Turbomachinery," AIAA Paper 2000-0884, *38th Aerospace Meeting and Exhibit*, 2000.

[43] K. Willcox, J. Peraire, and J. Paduano, "Application of Model Reduction to Compressor Aeroelastic Models," to appear in *J. of Turbomachinery*.

[44] B. Shapiro. "Solving for Mistuned Forced Response by Symmetry," *Journal of Propulsion and Power*, Volume 15 no. 2, pp. 310-325, 1999.

[45] G. L. Maahs. *Design of an active compressor blade for aeroelastic studies*. Master's thesis, MIT, 1999.

[46] J. Y. MHon.g *Application of a low-order model to assess compressor aeroelastic response and its control*. Master's thesis, MIT, 1999.

[47] W. A. MFarahat *Dynamical characterization, state estimation and testing of active compressor blades*. Master's thesis, MIT, 2000.

[48] S. Liao. *TBA*. PhD thesis, MIT, 2000.

[49] E. Nelson, J. Paduano, and A. Epstein, "Active Stabilization of Surge in an Axi-Centrifugal Turboshaft Engine," *J. of Turbomachinery*, Vol. 122, 2000.